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This report summarizes the research in the following areas: normal impact by blunt and 60° conically-tipped hard-steel 0.50 in diameter cylinders on Lexan, PMMA and nylon; oblique impact on Al, mild and hard steel targets up to ordnance velocities; Kelvar tests; ballistic limits, force measurements, controlled projectile tumbling, plate bending, impact on moving targets, yawing projectile impact on targets and numerical analysis.

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FINAL REPORT TO ARO: Contract DAAG29-84-K-0021

Submitted by Werner Goldsmith, Prof. of Mech. Engin., University of California, Berkeley, CA
Principal Investigator

Date: February 5, 1987 Contract Period: 1/23/84-1/22/87

ACTIVITY AND CURRENT STATUS: (a) Normal impact by blunt and 60° conically-tipped hard-steel 0.50 in diameter cylinders on Lexan, PMMA and nylon. More than 100 tests were conducted to determine the ballistic limit of Lexan alone, and combined targets of adjacent plates of Lexan and aluminum or steel of various thicknesses. The unusual phenomenon of bending in opposite directions of the initially adjacent metal and polymer plates. Tests with PMMA and nylon were not pursued due to lack of penetration resistance caused by brittle fracture of the substances. Experimental task for limited impact and target conditions is complete [1]; an expanded test program would be desirable, and a continuum-mechanical theory for these results is needed. (b) Oblique impact on aluminum, mild and hard steel targets up to ordnance velocities. More than 200 tests were conducted with both blunt and 60° conical-nosed hard-steel projectiles and with blunt soft aluminum cylindrical projectiles of 0.5 in diameter, with obliquities from zero to 50°. No further tests are currently contemplated [2,3]. (c) Normal and a very limited number of oblique impact tests on plates of alumina (AD 85 and AD 94, Coors Corp.), and combinations of adjacent or sandwiched plates of these ceramics and aluminum, steel, or Kevlar. Alumina and aluminum combinations have been subjected to normal projectile impact for a limited range of parameters [4,5]; further tests and a major analytical effort to explain striker abrasion and target response is urgently needed. Tests involving other combinations of a variety of ceramics and metallic and non-metallic backing or frontal layers would be highly desirable. Oblique impact on these material combinations should also be fully investigated. (d) Kevlar tests. A few exploratory ballistic tests of this material and some combinations have been executed. A complete and coherent series of impacts on this substance with both backing materials, prefacing plates and sandwich combinations should be undertaken, using various striker tips and speeds up to ordnance velocities. (e) Ballistic limit of monolithic vs layered adjacent aluminum targets. Normal impact of projectiles on these two types of targets shows that, for the range investigated, monolithic targets have a higher ballistic limit than layered adjacent plates of the same total thickness [1]. Additional tests of this type at higher velocities, with different and thicker materials should be undertaken. (f) Force measurement during oblique projectile impact on targets. Approximately 75 tests ranging from normal to 50° obliquity have been undertaken on steel and aluminum plates with both blunt and conically-tipped projectiles at speeds from 45-180 m/s. A quartz crystal with an inertial backing is embedded in the projectile in a fashion that the front and rear of crystal and striker are electrically isolated. A coil spring attached to the striker rear is fastened at the other end to the gun breech, which is grounded. The target is insulated, and the signal generated by the crystal is recorded on an oscilloscope with leads attached to the target and ground, respectively. The device is calibrated in numerous ways included the momentum change of the striker upon embedment in the target. Ten experiments also provided high-speed photographic coverage, and a dozen tests were conducted on nonmetallic targets (covered with an aluminum foil) at normal incidence. Development of the force transducer is complete [6,7], but the range of testing should be extended to higher velocities and other materials. (g) Controlled projectile tumbling. Thirty tests have been executed generating tumbling by impact of blunt-nosed strikers at normal incidence on the free edge of plates rigidly supported on the other three sides, using photographic coverage. The effect of this tumbling on a few targets stationed beyond the deflector plate was determined. An approximate theory of the deflector plate behavior and subsequent projectile motion has been developed, based on assumed plastic hinge geometries [8]. This work is in urgent need of further expansion and extension to ballistic speeds. (h) The phenomenon of plate bending near the ballistic limit has been investigated analytically and experimentally, the latter by conduct of 20 tests. Plastic hinges representing bending and shear effects in the target are superposed on a solution due to Liss executed under a previous ARO contract and constituting his doctoral dissertation. This work is in need of expansion to higher speeds and different materials, and supplementation of a finite element analysis of the process. The work represents a doctoral dissertation which is interrupted by the termination and non-renewal of the contract [9]. (i) Impact on moving targets. This has been successfully accomplished by precise synchronization of the firing of a pneumatic gun at circular aluminum targets rotating at the end of an arm driven by an electric motor. Extremely interesting petal forma-

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tions are observed depending on the ratio of projectile to target speed. Some progress has been made in initiating an analysis of this process. This task, which also constitutes a doctoral dissertation, is about half complete at this time, the termination of the contract [10]. It should not only be completed, but expanded to higher projectile and target velocities and a variety of different target materials. (j) Yawing projectile impact on targets. A few preliminary tests of this type have been performed, using a sabot with an angled slot with an inserted projectile. The tests are currently being analyzed. Major expansion of this program appears highly desirable, as well as comparisons with the results of target response of normal impact at the same translational velocity. (k) Numerical analysis. A substantial effort should be undertaken to provide two- and three-dimensional operational numerical codes for a description of the experimental phenomena observed in the tasks.

A complete ballistic facility has been generated by other DOD, private and University funding. Three powder guns with calibers of 38, 50 and 57 have been acquired, a nine-channel flash X-ray system is emplaced, two high-speed framing cameras and digital recording and processing equipment has been acquired.
The tasks cited above were performed over a 3-year period on a total budget of $260,000.

PERSONNEL:
Prof. W. Goldsmith, Principal Investigator; Dr. M. Mayseless, Visiting Scholar; J. Radin and Zvi Tauber, Associate Research Engineers; T. Jenq and E. Wu, Research Assistants and Ph. D. candidates; S. Virostek and O. Ruiz, Research Assistants and M. S. recipients; J. Dual, Research Assistant and M. Eng. recipient; engineering aides.

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